

Nonlinear Calculation Method of the Long Jib Structure with Big Slenderness Ratio based on Limit State Method

Gening Xu^{*1,a}, Qing Dong^{1,b}, Mingliang Yang^{1,c}, Huili Ren^{2,d}, Bin Zhang^{2,e}

¹School of Machinery and Electronics Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, China

²Academia Sinica, Zoomlion Heavy Industry Science and Technology Co. Lt, Changsha 410013, China

*^axugening@sina.com; ^bdongqing1989032800@126.com; ^cyangmingliang1977@163.com; ^drenhl@zoomlion.com;

^echinarencn0@163.com

Abstract

Aiming at large deformation, geometric, contact, material nonlinear and coupling for the structure of hectometer level elevating fire truck jib, limit state method is first adopted to design. In order to take into full consideration the impact of all kinds of load deviation value and discontinuity of materials from working grades classification, load states, load combination, material resistance and high risk coefficient to 3S (Strength, Stiffness, Stability) bearing capacity, load combination table, theoretical method and calculation flow are put forward through reference to the selection method of partial load factors, dynamic load coefficient, resistance coefficient and high risk coefficient of jib type crane. The quick and accurate calculation of bearing capacity of jib structure is achieved under different conditions and homologous poses (48 kinds of combination), which is based on the theoretical calculation software by using the VC++ development tools. In addition, with the help of finite element software (solidworks/simulation), the paper makes a simulative analysis of geometric, contact, material nonlinear and coupling of the jib. The results show that the results of theoretical calculations are in accordance with the finite element analysis results, which proves the correctness and feasibility of the load combination table and limit state method.

Keywords

Elevating Platform Fire Truck; Jib Structure; Limit State Method; Geometric; Contact and Material Nonlinear; Finite Element Analysis

Introduction

Along with the development of social economy, the demand for hectometer level elevating platform fire truck has been increasing in recent years with increase of the high-rise and super-high building constructions and rescue works. Heretofore, hybrid jib structure has been used in the field of telescopic jib structure of large elevating platform fire truck, while domestic research on that is at its early stage. The current design method

for the structure of elevating platform fire truck under 100 meters is the allowable stress method from the current nation criteria "Standard on Elevating platform fire truck". The jib structure of 101 meters elevating platform is calculated with theoretical calculation based on the allowable stress method in the two available papers. It has been shown from the study results that the calculation results have certain gap with the experimental, resulting from the fact that super-long jib structure is easy to be affected by large deformation, geometric, contact, material nonlinear and coupling. The limit state design method on the basis of the theory of probability has been put forward in GB/T3811-2008 "Design rules for crane". Compared with the traditional allowable stress method, the limit state method is more suitable for the internal force and load into nonlinear occasions. Therefore, it is scientific and a tendency to apply the limit state method to solve problems of nonlinear and coupling for designing hectometer grade (113 meters-the highest jib in the world so far) elevating platform fire truck jib structure.

Limit State Method



Load combination Internal Force Stress

FIG. 1 TYPICAL FLOW CHAT OF LIMIT STATE METHOD

The limit state method is a kind of design method to make the stress and deformation which are produced by load on the structure and connection joint less than the ultimate bearing capacity. The importance of different loads, the material to the bearing capacity and the influence of high risk have been taken into account in calculating process with this method. The calculation procedures are showed in Figure 1.

1) f_i for individual specified or characteristic loads is calculated and amplified when necessary using the corresponding dynamic coefficient φ_i multiplied by the appropriate partial load coefficient values γ_{pi} .

2) f_i is combined based on the load combination according to the actual conditions under consideration to give the combined load F_j . If appropriate, the high risk coefficient γ_n is applied to the combined load F_j to give the design load $\gamma_n F_j$, otherwise, next step.

3) Design load effects S_k are determined from the design load.

4) The stresses σ_{li} due to the action of the load effects on a particular element or component are calculated and combined with any stresses σ_{2li} , resulting from local effects which have also been calculated using the appropriate load coefficients.

5) The resulting design stress σ_i should be compared with an appropriate limit value $\lim \sigma$, which can be taken as follows:

$$\lim \sigma = R / \gamma_m \quad (1)$$

where R is the specified strength or characteristic resistance of the material, particular element or connection, such as the stress corresponding to the yield point, limit of elastic stability or fatigue strength (limit states), γ_m is the resistance coefficient.

Load and Load Combination

It is impossible for loads acting on an elevating platform

fire truck at the same time, therefore, loads that likely appeared simultaneously should be combined under considering the odds of getting payloads and the worst influence on the jib structure under different working conditions and characteristics of elevating platform fire trucks. According to the load combination method of jib type crane, loads and load combination for the limit state method together with applicable partial load factors γ_p , dynamic amplification factor φ_n , resistance coefficient γ_m and high-risk coefficient γ_n are given in table 1, which is suitable for elevating platform fire truck.

Mechanical Analysis

Hybrid telescopic polygon structures are adopted by the system of jib for hectometer level elevating platform fire truck, mainly including jib of No.1, jib of No.2 and flying jib. Jib of No.1 is used for lifting. Jib of No.2 can realize amplitude with the four-bar linkage and lift cylinder. The root and head of No.1 are connected with the hinge. Flying jib and 3 section jib of No.2 also have been together with the hinge device, as shown in figure 2.

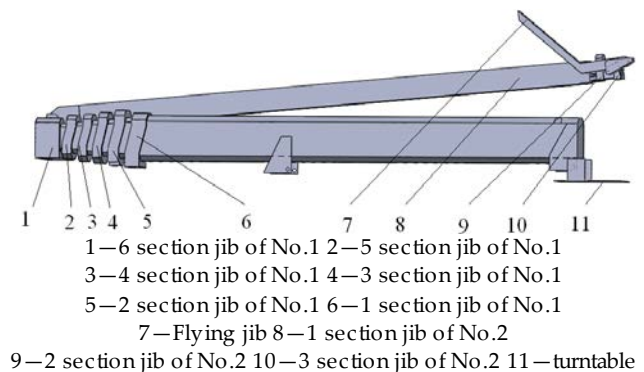


FIG. 2 SKETCH OF AERIAL PLATFORM FIRE TRUCK JIB

TABLE 1 LOAD AND LOAD COMBINATIONS OF ELEVATING PLATFORM FIRE TRUCK JIB STRUCTURE BASED ON LIMIT STATE METHOD

Loads, f_i			Load combinations A					Load combinations B					
			partial load factors γ_p	A1	A2	A3	A4	partial load factors γ_p	B1	B2	B3	B4	B5
Gravity, acceleration, impacts	Mass of the lifting appliance		$\gamma_{PA1} = 1.16$	φ_1	φ_1	1	—	$\gamma_{PB1} = 1.16$	φ_1	φ_1	1	—	—
	Mass of the grass load		$\gamma_{PA2} = 1.34$	φ_2	φ_3	1	—	$\gamma_{PB2} = 1.28$	φ_2	φ_3	1	—	—
Acceleration from drives	Mass of lifting appliance and grass load	Hoist drives excluded	$\gamma_{PA3} = 1.55$	φ_5	φ_5	—	φ_5	$\gamma_{PB3} = 1.48$	φ_5	φ_5	—	φ_5	—
		Hoist drives included	$\gamma_{PA4} = 1.55$	—	—	φ_5	—	$\gamma_{PB4} = 1.48$	—	—	φ_5	—	—
In-service wind loads			—	—	—	—	—	$\gamma_{PB5} = 1.16$	1	1	1	1	1
Manual load			1	1	1	1	1	1	1	1	1	1	1
Water impact load			$\gamma_{PA6} = 1.34$	φ_2	φ_3	1	—	$\gamma_{PB6} = 1.28$	φ_2	φ_3	1	—	—
Mass of the water			$\gamma_{PA7} = 1.34$	φ_2	φ_3	1	—	$\gamma_{PB7} = 1.28$	φ_2	φ_3	1	—	—
Resistance coefficient			$\gamma_m=1.1$										
High-risk coefficient			$\gamma_n=1.1$										

Because of the particularity of linking modes among jib of No.1, jib of No.2 and flying jib, taking the most unfavorable load combination in a certain condition for example, each of them as a research object is conducted through mechanical analysis. The strength, stiffness and stability of calculation formula, based on the mechanical analysis jib of No.2, are given in the paper and the calculation method of flying jib and jib of No.1 is similar with No.2.

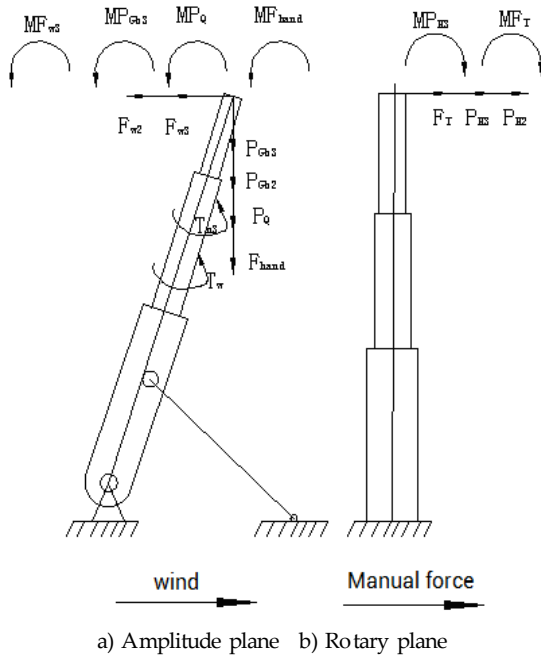


FIG. 3 FORCE SKETCH OF ARM OF NO.2

Jib of No.2 is a jib structure which bears vertical loads, horizontal loads, and torque loads and additional bending moment. Vertical loads include P_Q for the rated load, P_{Gb3} for load of flying jib structure weight, P_{Gb2} for load of jib of No.2 structure weight and F_{hand} for manual load. Horizontal loads include F_{w3} for in-service wind load of flying jib, F_{w2} for in-service wind load of jib of No.2. Additional bending moments include MP_Q produced by the rated load, MP_{Gb3} produced by load of flying jib structure weight, MF_{w3} produced by in-service wind load of flying jib and MF_{hand} produced by manual load. Horizontal loads include F_T for the deflection force of the goods, P_{H3} for rotary inertia force of flying jib and P_{H2} for rotary inertia force of jib of No.2 in rotary plane. Additional bending moments include items for MF_T produced by the deflection of goods and MP_{H3} for fly jib's rotary bending moment. Torque loads include the items produced by the deflection of the torque T_w and T_{n3}

for the additional torque of flying jib offset. The specific forces for the mechanical analysis of No.2 are shown in Figure 3.

The external force of the structure of the jib in amplitude plane is shown in figure 3 a). The computation loads based on limit state method are given, according to table 1 B1 combination. Subsequently, the axial force and shear force are obtained through decomposition into forces along the axial of jib and vertical to the jib. Meanwhile, the total additional bending moment is synthesized by each of additional bending moment.

The axial force is:

$$N = \gamma_n \{ [\gamma_{pB2} \phi_2 P_Q + \gamma_{pB1} \phi_1 (P_{Gb3} + P_{Gb2}) + F_{hand}] \sin a_2 + \gamma_{pB5} (F_{w3} + F_{w2}) \cos a_2 \} \quad (2)$$

where a_2 is the amplitude angle of jib of No.2.

The shear force is:

$$p_y = \gamma_n \{ [\gamma_{pB2} \phi_2 P_Q + \gamma_{pB1} \phi_1 (P_{Gb3} + P_{Gb2}) + F_{hand}] \cos a_2 - \gamma_{pB5} (F_{w3} + F_{w2}) \sin a_2 \} \quad (3)$$

Total additional bending moment in amplitude plane is:

$$M_{Lx} = \gamma_n (\gamma_{pB2} \phi_2 MP_Q + \gamma_{pB1} \phi_1 MP_{Gb3} + MF_{hand} + \gamma_{pB5} MF_{w3}) \quad (4)$$

The external force of the structure of the jib in rotary plane is shown in figure 3 b). The horizontal force of the jib is:

$$P_{x3} = \gamma_n [\gamma_{pB2} F_T + \gamma_{pB3} \phi_5 (P_{H3} + P_{H2})] \quad (5)$$

Total additional bending moment in rotary plane is:

$$M_{Ly} = \gamma_n (\gamma_{pB3} \phi_5 MP_{H3} + \gamma_{pB2} MF_T) \quad (6)$$

Stiffness, Strength and Stability Calculation of Telescopic Jib

It is important for the stiffness, strength and stability of metal structure to be indicators to identify the effectiveness of components. Therefore, in the course of conduction of the structure calculation, the calculation theory for the jib structure in accordance with the actual situation for large slenderness ratio, smaller stiffness for the jib is not conformity the assumption of small deformation for torsion and flexure. Consequently, the structural nonlinear large deformation theory which is used to calculate the strength, stiffness and stability of the jib structure for hectometer level elevating platform fire truck, is more accurate than the linear theory.

The basic displacement produced by the telescopic jib of No.2 under the action of external loads static is

composed of the displacement of telescopic jib head caused by the gap in groove board joint and the static displacement caused by horizontal force and bending moment, multiplied by the nonlinear amplification coefficient; while the actual displacement is multiplied by a nonlinear coefficient on the basis of the static displacement.

The actual displacement in amplitude plane can be taken as follows:

$$f_y = \frac{1}{(1 - N/N_{Ex})} (f_{wy} + f_{jy}) \leq [Y_L] \quad (7)$$

where f_{jy} is the displacement of telescopic jib head caused by the gap in groove board joint in amplitude plane, f_{wy} is the static displacement of telescopic jib head caused by horizontal force and bending moment in amplitude plane, N is the axial force of the jib, N_{Ex} is the critical force in amplitude plane, $[Y_L]$ is the allowable displacement in amplitude plane.

The actual displacement in rotary plane can be taken as follows:

$$f_x = \frac{1}{(1 - N/N_{Ey})} (f_{wx} + f_{jx}) \leq [X_L] \quad (8)$$

where f_{jx} is the displacement of telescopic jib head caused by the gap in groove board joint in rotary plane, f_{wx} is the static displacement of telescopic jib head caused by horizontal force and bending moment in rotary plane, N_{Ey} is the critical force in rotary plane, $[X_L]$ is the allowable displacement in rotary plane.

Because the guide sliders of telescopic jib bear greater concentrated forces, which leads to an uneven distribution of the stress in the sliders, the local bending stress is produced on the flange plate near the sliders. When making strength calculations, the stress of the overlapping parts should also be calculated except for calculating the stress of non overlapping parts. For non overlapping parts, the maximum stress of arbitrary cross section is as follows:

$$\sigma(z) = 1.1 \left[\frac{M_x(z)}{(1 - N/N_{Ex})W_x(z)} + \frac{M_y(z)}{(1 - N/N_{Ey})W_y(z)} \right] \leq \lim \sigma \quad (9)$$

where $M_x(z)$ is the basic moment of the section z produced by the full load of telescopic jib in amplitude plane, $M_y(z)$ is the basic moment of the section z produced by the full load of telescopic jib in rotary plane, $W_x(z)$ is section modulus in bending of the telescopic jib section to the x axis, $W_y(z)$ is section modulus in bending of the telescopic jib section to the y axis, $\lim \sigma$ is a ultimate stress value.

Considering the effect of restrained bending and constrained torsion in the cross section of the jib, the strength calculation values should be amplified by 1.1.

For overlapping, first of all, supporting force of each guide slider should be obtained, caused by the bending moment of the jib head and the lateral force, in the bottom flange plate, and then according to supporting force, the local bending stress near the slider is calculated, finally the resultant stress is obtained through combining the global bending stress near slide with local bending stress. The pair of sliders bears the largest force as shown in figure 4.

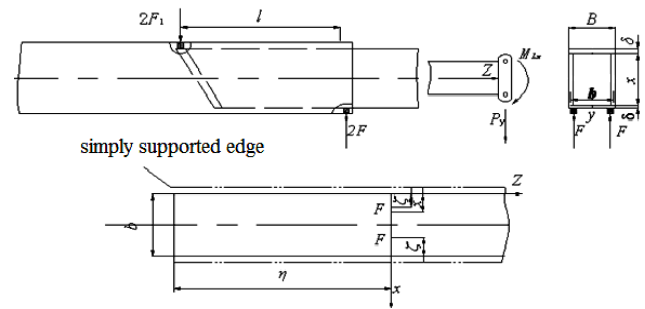


FIG. 4 FORCE SKETCH OF FLANGE PLATE PRODUCED BY GUIDE SLIDERS

The supporting force of each slider is:

$$F = 0.5 \left[M_x(z) / l + P_y \right] \quad (10)$$

where l is the distance between the former and the latter slider along the jib direction, $M_x(z)$ is the moment of a cross section, P_y is the lateral force.

The calculation formula of the local bending stress of the flange plate for the telescopic jib is:

$$\sigma_{zj} = \sigma_{xj} = k \frac{3F(1+\mu)}{4\pi\delta_0^2} \ln \left\{ \left[\frac{1 - \cos \frac{\pi(x+\xi)}{b}}{1 - \cos \frac{\pi(x-\xi)}{b}} \right] \left[\frac{1 + \cos \frac{\pi(x-\xi)}{b}}{1 + \cos \frac{\pi(x+\xi)}{b}} \right] \right\} \quad (11)$$

where k is a correction coefficient used to consider the difference between theoretical and the actual calculation, ξ is the slider midpoint location, as shown in figure 3, x is the position of the calculation points, which can't select the slider neutral position, That is, $x \neq \xi$, δ_0 is the flange plate thickness, b is the distance of centerlines of two webs, μ is Poisson's ratio.

The resultant stress of the flange plate calculation formula is:

$$\sigma = \sqrt{(\sigma_z + \sigma_{zj})^2 + \sigma_{xj}^2 - (\sigma_z + \sigma_{zj})\sigma_{xj} + 3\tau^2} \leq \lim \sigma \quad (12)$$

where σ_z is the global bending stress of the calculation point of the flange along the z direction

near sliders, which is calculated according to the increasing coefficient method of the nonlinear theory, σ_{zj} is the local bending stress of the calculation point of the flange near sliders, τ is the shear stress of the calculation point of the flange near sliders.

The global structure stability calculation must be carried out as one part of the structure theoretical calculation because it is easy to be instability, which is attributed to over length and the higher slenderness ratio for the jib.

The effect of initial defect of the axial compression part is excluded from consideration in the process of the stability calculation of the jib because of the particularity of the structure, but $N(f_j + f_L)$ for bending moment produced by f_j for the initial displacement on the tip of the jib caused by the gap and f_L for the basic dynamic displacement caused by the external force should be appended to the corresponding bending moment. At the same time limit state method is utilized to calculate the global stability of the hydraulic components, N_{Ex} and N_{Ey} should be divided by the resistance coefficient γ_m . The computation formula is as follows:

$$\sigma = \frac{N}{A} + \frac{M_x}{(1-\gamma_m N/N_{Ex})W_x} + \frac{M_y}{(1-\gamma_m N/N_{Ey})W_y} \leq \lim \sigma \quad (13)$$

The calculation software is designed according to the calculation theory and the object-oriented and modular program design principle of VC++6.0, which is used to calculate the strength, stiffness and stability of the structure. Finally, the results for the calculation are displayed in the dialog box.

Finite Element Analysis

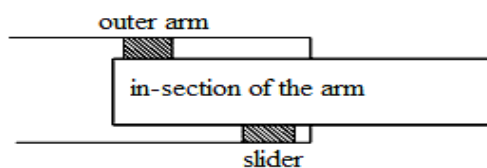


FIG. 5 SKETCH OF LAP JOINTING TYPE FOR SLIDERS

Solidworks/simulation for finite element software is used to build and analyze the three-dimensional

modeling of the structure of the jib for 113 meters elevating platform fire truck.

Simplified Model

Shell element is employed to establish respective model for jib of No.1, No.2 and flying jib and solid element to model slides, then according to the actual location, they are assembled to study as a whole. The type of lap jointing for sliders is simplified as shown in figure 5.

Constraint Handling

According to the actual work situation, translation in three directions and rotation for x and y are constrained in the hinge joint region between turntable and jib of No.1. Other hinge joint regions are the same. The position of the pin connection applies the coupling of three directions and the rotation for x and y.

All loads role in the jib structure should be according to the direction of the actual load, meanwhile, the wind load and load of jib structure as distributed load and the rated load as a concentrated load act on the structure.

Results and Analysis

The jib structure of 113 meters elevating platform fire truck is taken as an example. The specific conditions and poses of the jib are input back into the visual interface of VC++6.0, and the theoretical calculation results is obtained by the calculating program. At the same time, it is analyzed by finite element software on the basis of confirming loads of working conditions according to the load combination.

Theoretical Calculation Results

The calculation results for one operating mode and the corresponding position of 48 kinds of combined are given in this paper (450 kg for rated load, 12.5 m/s for wind speed, 400 N for manual load, the direction of the loads can be seen in figure 2). The calculation process of other working conditions and the analysis method of results are similar.

TABLE 2 CALCULATION RESULTS BASED ON LIMIT STATE METHOD

Item	Flying jib		Jib of No.2		Jib of No.1	
	maximum value	limit value	maximum value	limit value	maximum value	limit value
Displacement for amplitude plane(mm)	2.7	11.2	573	1708	597	4632
Displacement for rotary plane(mm)	0.7	7.84	410	1196	818	3242
Strength for non overlapping parts(MPa)	52.2	809	287.70	809	285.28	809
Strength for overlapping parts(MPa)	—		333.47		251.30	
Global Stability(MPa)	54.8		165.74		199.87	

TABLE 3 COMPARISON RESULTS OF THEORETICAL CALCULATION AND FINITE ELEMENT ANALYSIS

Item	Jib	Flying jib			Jib of No.2			Jib of No.1		
		theoretical value	analysis result	error	theoretical value	analysis result	error	theoretical value	analysis result	error
Displacement for amplitude plane(mm)		1173	1231	4.7%	1170	1191	1.8%	597	607	1.6%
Displacement for rotary plane(mm)		1229	1252	1.9%	1228	1261	2.6%	818	862	5.1%
resultant displacement(mm)		1699	1756	3.2%	1696	1734	2.2%	1013	1054	3.9%
Strength for non overlapping parts (MPa)		52.2	51.0	2.3%	287.70	283.1	1.6%	285.28	280.1	1.8%
Strength for overlapping parts(MPa)		—	—	—	333.47	328.3	5.17	251.30	243.5	3.2%

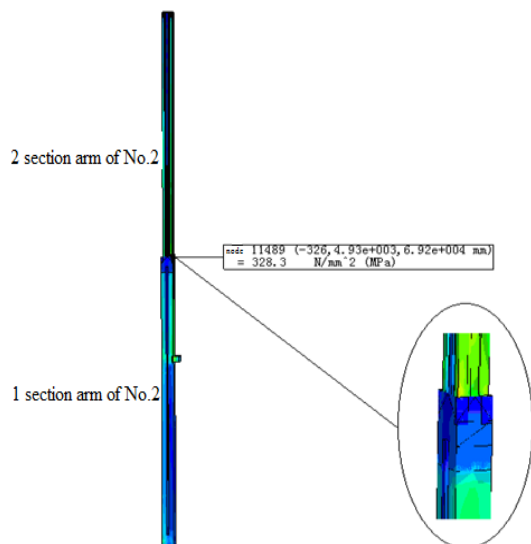


FIG. 7 MAXIMUM STRESS, POSITION OF JIB OF NO.2

The calculation results for flying jib, jib of No.1 and No.2 are given, based on limit state method, as shown in table 3.

Fly jib, jib of No.1 and No.2 are regarded as the research object respectively in the process of theoretical calculation, so the displacements are relative displacements of the each root. Using the vector synthesis method, the results of the displacement of elevating platform fire truck jib can be acquired. The total displacement is 1173 mm in amplitude plane and 1229 mm in rotary plane. The resultant displacement is 1699 mm.

The location of the maximum stress for flying jib is in the hinge joint section of its lift cylinder. The location of the maximum stress for jib of No.2 is in the lap jointing between its first and second jib. The location of the maximum stress for jib of No.1 is near its sixth head.

Finite Element Analysis Result

Through using finite element analysis software to analyze the jib structure, the maximum stresses, 51.0 MPa for the flying jib, 328.3 MPa for jib of No.2 and 280.1 MPa for jib of No.1 are achieved, and the corresponding positions are given. (flying jib in figure 6, jib of No.2 in figure 7, jib of No.1 in figure 8) The

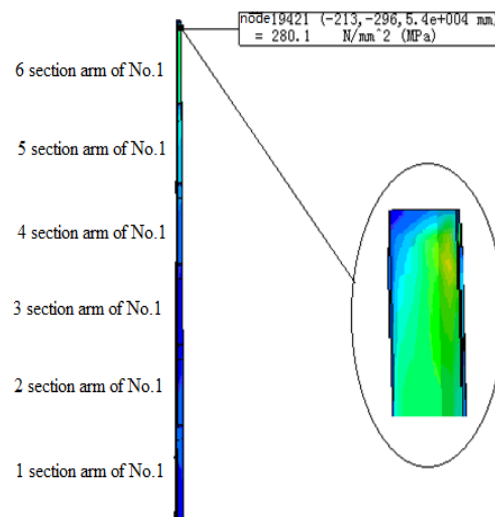


FIG. 8 MAXIMUM STRESS, POSITION OF JIB OF No.1

resultant displacement is 1756 mm.

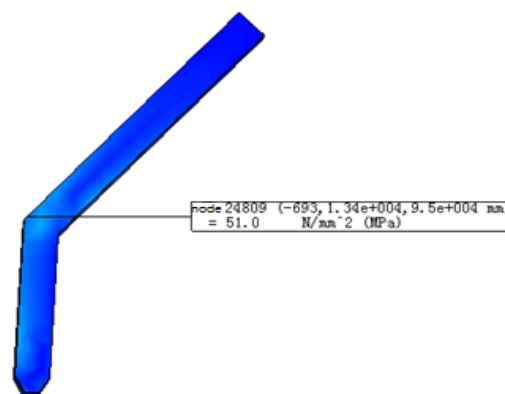


FIG. 6 MAXIMUM STRESS, POSITION OF THE FLYING JIB

Contrasting and Analyzing Result

As shown in table 3, the results of theoretical calculation and finite element analysis are given.

The theoretical results of the stress are slightly greater than the finite element analysis results. The largest stress difference value is 1.2 MPa for flying jib, 5.17 MPa for jib of No.2 and 5.18 MPa for jib of No.1, as shown in table 3. The gap is mainly caused by the different simplified way of the model and loads. The theoretical calculation relies on flying jib, jib of No.2 and No.1 respectively as the research object and one third of the weight of jib and wind loads as a

concentrated load act on its head region. gravity load and wind load both as uniform loads act on the whole jib when applying finite element software to analyze. The locations of the each maximum stress by theoretical calculation essentially agrees with the location results obtained from finite element software. The theoretical displacement values are less than those obtained from finite element analysis and the biggest difference value is 57 mm (see table 3). The reason for this is that the difference is considered between the slider and jib material when using the finite element software to analyze the jib but the theoretical calculation fails to consider the factor of different materials.

Conclusions

- 1) Limit state method based on the theory of probability can fully consider the different of loads, material of the structure and conditions for the elevating platform fire truck jib to use partial load factors instead of the single safety coefficient to calculate the strength, stiffness and stability. The calculating results agree with the actual situation.
- 2) As shown in table 3, the theoretical calculation results essentially agree with those of finite element analysis. The maximum error is less than 5.1%; and the minimum is 1.6%. The results verify the accuracy of load and load combinations and the feasibility of limit state method in the design field of nonlinear large deformation design of elevating platform fire truck structure.
- 3) It is a significant breakthrough in structural design for hectometer level elevating platform fire truck which is beyond the scope of national standards, at the same time, the concrete design method has been obtained.

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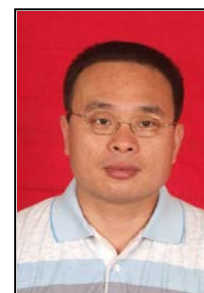
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Gening Xu, (Hubei, 1955), male, Chinese, Dr. of Mechanical Engineering, Professor, field of research: Mechanical structures 3D-modeling, CAD/CAE system integration, Reliability failure analysis, Safety assessment,
Email: xugening@sina.com



Qing Dong, (Shanxi, 1989), female, Chinese, A Graduate Student of Mechanical Design and Theory, field of research: Design method of the Great Length Jib Structure for Elevating Platform Fire Truck,
Email: dongqing1989032800@126.com



Mingliang Yang, (Shanxi, 1989), male, Chinese, Dr. of Mechanical Engineering, Associate Professor, field of research: Mechanical structures CAD/CAE system integration and simulation,
Email: yangmingliang1977@163.com



Huili Ren, (Shandong, 1977), male, Chinese, Dr. of Mechanical Engineering, Senior Engineer, field of research: Mechanical structures reliability and fatigue failure analysis, Safety assessment,

Email: renhl@zoomlion.com



Bin Zhang, (Hubei, 1981), male, Chinese, Ms. of Mechanical structures reliability and fatigue failure analysis, Email: chinarencn0@163.com